

ABOUT SUPERPARTNERS AND THE ORIGINS OF THE SUPERSYMMETRIC STANDARD MODEL

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We recall the obstacles which seemed, long ago, to prevent supersymmetry from possibly being a fundamental symmetry of Nature. Which bosons and fermions could be related? Is spontaneous supersymmetry breaking possible? Where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry? Can one define conserved baryon and lepton numbers in such theories, although they systematically involve self-conjugate Majorana fermions? etc.. We then recall how an early attempt to relate the photon with a “neutrino” led to the definition of R -invariance, but that this “neutrino” had to be reinterpreted as a new particle, the *photino*. This led us to the Supersymmetric Standard Model, involving the $SU(3) \times SU(2) \times U(1)$ gauge interactions of chiral quark and lepton superfields, and of two doublet Higgs superfields responsible for the electroweak breaking and the generation of quark and lepton masses. The original continuous R -invariance was then abandoned in favor of its discrete version, R -parity – reexpressed as $(-1)^{2S} (-1)^{(3B+L)}$ – so that the gravitino and gluinos can acquire masses. We also comment about supersymmetry breaking.

1 Introduction

The algebraic structure of supersymmetry in four dimensions was introduced in the beginning of the seventies by Gol’fand and Likhtman¹, Volkov and Akulov², and Wess and Zumino³, as recalled in various contributions to this book. It involves a spin- $\frac{1}{2}$ fermionic symmetry generator, called the supersymmetry generator, satisfying anticommutation relations. This supersymmetry generator Q is defined so as to relate fermionic with bosonic fields, in supersymmetric relativistic quantum field theories.

At that time it was not at all clear if – and even less how – supersymmetry could actually be used to relate fermions and bosons, in a physical theory of particles. While very interesting from the point of view of relativistic field theory, supersymmetry seemed clearly inappropriate for a description of our physical world. In particular one could not identify physical bosons and fermions that might be related under such a symmetry. It even seemed initially that supersymmetry could not be spontaneously broken at all – in contrast with ordinary symmetries – which would imply that bosons and fermions be systematically degenerated in mass! Supersymmetric theories also involve, systematically, self-conjugate Majorana spinors – unobserved in Nature – while the fermions that we know all appear as Dirac fermions carrying conserved (B and L) quantum numbers. In addition, how could we account for the conservation of the fermionic

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numbers B and L (only carried by fermions), in a supersymmetric theory, in which fermions are related to bosons? Most physicists were then considering supersymmetry as irrelevant for “real physics”.

Still this algebraic structure could actually be taken seriously as a possible symmetry of the physics of fundamental particles and interactions, once we understood that the above obstacles preventing the application of supersymmetry to the real world could be overcome. After an initial attempt illustrating how far one could go in trying to relate known particles together, in particular the photon with a “neutrino”, and the W^\pm bosons with charged “leptons” – and the limitations of this approach – in a spontaneously broken $SU(2) \times U(1)$ electroweak theory involving two chiral doublet Higgs superfields⁴, we were quickly led to reinterpret the fermions of this model, which all possess a conserved R quantum number carried by the supersymmetry generator, as belonging to a new class of particles. The “neutrino” ought to be considered as a really new particle, a “photonic neutrino”, a name which I transformed in 1977 into *photino*, also calling at the same time *gluinos* the fermionic partners of the colored gluons (quite distinct from the quarks!), and so on. More generally this led us to postulate the existence of new R -odd “superpartners” for all ordinary particles and consider them seriously, despite their rather non-conventional properties: e.g. new bosons carrying “fermion” number, now known as *sleptons* and *squarks*, or Majorana fermions transforming as an $SU(3)$ color octet, which are precisely the *gluinos*, etc.^{5,6}. In addition the electroweak breaking must be induced by a *pair* of electroweak Higgs doublets, not just a single one as in the Standard Model, which requires the existence of *charged Higgs bosons*, and of several neutral ones.

The still-hypothetical superpartners may be distinguished by a new quantum number called R -parity⁷, associated with a Z_2 remnant of the continuous R -symmetry, which may be multiplicatively conserved in a natural way, and is especially useful to guarantee the absence of unwanted interactions mediated by squark or slepton exchanges. The conservation (or non-conservation) of R -parity is closely related with the conservation (or non-conservation) of baryon and lepton numbers, B and L , as illustrated by the well-known formula reexpressing R -parity as $(-1)^{2S} (-1)^{3B+L}$ ⁸. The finding of the basic building blocks of what we now call the Supersymmetric Standard Model (whether “minimal” or “non-minimal”) allowed for the experimental searches for “supersymmetric particles”, which started with the first searches for gluinos and photinos, selectrons and smuons, in the years 1978-1980, and have been going on continuously since. These searches often rely on the “missing energy” signature, corresponding to energy-momentum carried away by unobserved neutralinos^{5,8,9,10}. A conserved R -parity also ensures the stability of the “lightest supersymmetric particle”, a good candidate to constitute the non-baryonic Dark Matter that seems to be present in our Universe. The general opinion of the scientific community towards supersymmetry and supersymmetric extensions of the Standard Model has considerably changed since the early days, and it is now widely admitted that supersymmetry may well be the next fundamental symmetry to be discovered in the physics of fundamental particles and interactions, although this remains to be experimentally proven.

2 Nature does not seem to be supersymmetric !

Let us now travel back in time, and think about the supersymmetry algebra, and the way it might be realized in Nature. This supersymmetry algebra

$$\left\{ \begin{array}{l} \{ Q, \bar{Q} \} = -2 \gamma_\mu P^\mu \ , \\ [Q, P^\mu] = 0 \ . \end{array} \right. \quad (1)$$

was introduced, in the years 1971-1973, by three different groups, with quite different motivations. Gol’fand and Likhtman¹, in their remarkable work published in 1971, first introduced it with the apparent hope of understanding parity-violation: when the Majorana supersymmetry generator Q_α is written as a two-component chiral Dirac spinor (say Q_L), one may have the impression that the supersymmetry algebra, which then involves a chiral projector in the right-handside of the anticommutation relation (1), is intrinsically parity-violating (which, however, is not the case); they suggested that such (supersymmetric) models must therefore necessarily violate parity, probably thinking that this could lead to an explanation for parity-violation in weak interactions. Volkov and Akulov² hoped to explain the masslessness of the neutrino from a possible interpretation as a spin- $\frac{1}{2}$ Goldstone particle, while Wess and Zumino³ wrote the algebra by extending to four dimensions the “supergauge” (i.e. supersymmetry) transformations¹¹, and algebra¹², acting on the two-dimensional string worldsheet. However, the mathematical existence of an algebraic structure does not imply that it has to play a rôle as an invariance of the fundamental laws of Nature^b.

Indeed many obstacles seemed, long ago, to prevent supersymmetry from possibly being a fundamental symmetry of Nature. Which bosons and fermions could be related by supersymmetry? May be supersymmetry could act at the level of composite objects, e.g. as relating baryons with mesons? Or should it act at a fundamental level, i.e. at the level of quarks and gluons? (But quarks are color triplets, and electrically charged, while gluons transform as an $SU(3)$ color octet, and are electrically neutral!) Is spontaneous supersymmetry breaking possible at all? If yes, where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry, if it cannot be identified as one of the known neutrinos? Can we use supersymmetry to relate directly known bosons and fermions? And, if not, why? If known bosons and fermions cannot be directly related by supersymmetry, do we have to accept this as the sign that supersymmetry is *not* a symmetry of the fundamental laws of Nature? If we still insist to work within the framework of supersymmetry, how could it be possible to define conserved baryon and lepton numbers in such theories, which systematically involve *self-conjugate* Majorana fermions, unknown in Nature, while B and L are carried only by fundamental (Dirac) fermions – not by bosons? And, once we are finally led to postulate the existence of new bosons carrying B and L – the new spin-0 squarks and sleptons – can we prevent them from mediating new unwanted interactions?

While bosons and fermions should have equal masses in a supersymmetric theory, this is certainly not the case in Nature. Supersymmetry should then clearly be broken. But spontaneous supersymmetry breaking is notoriously difficult to achieve, to the point that it was even initially thought to be impossible! Why is it so? Supersymmetry is a special symmetry, since the Hamiltonian, which appears in the right-handside of the anticommutation relations (1), can be expressed proportionally to the sum of the squares of the components of the supersymmetry generator, as $H = \frac{1}{4} \sum_\alpha Q_\alpha^2$. This implies that a supersymmetry preserving vacuum state must have vanishing energy¹³, while any candidate for a “vacuum state” which would not be invariant under supersymmetry may naïvely be expected to have a larger, positive, energy^c. As a

^bIncidentally while supersymmetry is commonly referred to as “relating fermions with bosons”, its algebra (1) does not even require the existence of fundamental bosons! (With non-linear realizations of supersymmetry a fermionic field can be transformed into a *composite* bosonic field made of fermionic ones²; but we shall work within the framework of the linear realizations of the supersymmetry algebra, which allows for renormalizable supersymmetric field theories.) The supersymmetry algebra (1) certainly does not imply by itself the existence of the superpartners! (Just as the mathematical existence of the $SU(2)$ group does not imply the physical existence of the isospin or electroweak symmetries, the existence of $SU(3)$ does not imply that of the strange quark, and the flavor or color symmetries; the existence of $SU(4)$ does not require technicolor, nor that of $SU(5)$, grand unification!)

^cSuch a would-be supersymmetry breaking state corresponds, in global supersymmetry, to a *strictly positive*

result, potential candidates for supersymmetry breaking vacuum states seemed to be necessarily unstable, leading to the question:

Q1 : *Is spontaneous supersymmetry breaking possible at all ?* (2)

As it turned out, and despite the above argument, several ways of breaking spontaneously global or local supersymmetry have been found^{14,15,16}. But spontaneous supersymmetry breaking remains, in general, rather difficult to obtain, since theories tend to prefer, for energy reasons, supersymmetric vacuum states. Only in very exceptional situations can the existence of such states be completely avoided!

As explained above in global supersymmetry a non-supersymmetric state has, in principle, always more energy than a supersymmetric one; it then seems that it should always be unstable, the stable vacuum state being, necessarily, a supersymmetric one! Still it is possible to escape this general result – and this is the key to spontaneous supersymmetry breaking – if one can arrange to be in one of those rare situations for which *no supersymmetric state exists at all* – the set of equations for the auxiliary field v.e.v.'s $\langle D \rangle' = \langle F \rangle' = \langle G \rangle' = 0$ having *no solution at all*. But these situations are in general quite exceptional. (This is in sharp contrast with ordinary symmetries, in particular gauge symmetries, for which one only has to arrange for non-symmetric states to have less energy than symmetric ones, in order to get spontaneous symmetry breaking.) These rare situations usually involve an abelian $U(1)$ gauge group¹⁴, allowing for a gauge-invariant linear “ ξD ” term to be included in the Lagrangian density^d; and/or an appropriate set of chiral superfields with special superpotential interactions which must be very carefully chosen (so as to get “ F -breaking”)¹⁵, preferentially with the help of additional symmetries such as R -symmetries. In local supersymmetry¹⁷, which includes gravity, one also has to arrange, at the price of a very severe fine-tuning, for the energy density of the vacuum to vanish exactly¹⁶, or almost exactly, to an extremely good accuracy, so as not to generate an unacceptably large value of the cosmological constant Λ .

Whatever the mechanism of supersymmetry breaking, we have to get – if this is indeed possible – a physical world which looks like ours (which will precisely lead to postulate the existence of superpartners for all ordinary particles). Of course just accepting the possibility of explicit supersymmetry breaking without worrying too much about the origin of supersymmetry breaking terms, as is frequently done now, makes things much easier – but also at the price of introducing a large number of arbitrary parameters, coefficients of these supersymmetry breaking terms. In any case such terms must have their origin in a spontaneous supersymmetry breaking mechanism, if we want supersymmetry to play a fundamental role, especially if it is to be realized as a local fermionic gauge symmetry, as in the framework of supergravity theories. We shall come back to this question of supersymmetry breaking later. In between, we note that the spontaneous breaking of the global supersymmetry must in any case generate a massless spin- $\frac{1}{2}$ Goldstone particle, leading to the next question,

Q2 : *Where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry ?* (3)

Could it be one of the known neutrinos²? A first attempt at implementing this idea within a $SU(2) \times U(1)$ electroweak model of “leptons”⁴ quickly illustrated that it could not be pursued

energy density – the scalar potential being expressed proportionally to the sum of the squares of the auxiliary D , F and G components, as $V = \frac{1}{2} \sum (D^2 + F^2 + G^2)$.

^dEven in the presence of such a term, one frequently does not get a spontaneous breaking of the supersymmetry: one has to be very careful so as to avoid the presence of supersymmetry restoring vacuum states, which generally tend to exist.

very far. (Actually, the “leptons” of this first electroweak model were soon to be reinterpreted to become the “charginos” and “neutralinos” of the Supersymmetric Standard Model.)

If the Goldstone fermion of supersymmetry is not one of the known neutrinos, why hasn’t it been observed? Today we tend not to think at all about the question, since: 1) the generalized use of soft terms breaking *explicitly* the supersymmetry seems to make this question irrelevant; 2) since supersymmetry has to be realized locally anyway, within the framework of supergravity¹⁷, the massless spin- $\frac{1}{2}$ Goldstone fermion (“goldstino”) should in any case be eliminated in favor of extra degrees of freedom for a massive spin- $\frac{3}{2}$ gravitino^{6,16}.

But where is the gravitino, and why has no one ever seen a fundamental spin- $\frac{3}{2}$ particle? Should this already be taken as an argument against supersymmetry and supergravity theories? Or should one consider that the crucial test of such theories should be the discovery of a spin- $\frac{3}{2}$ particle? In that case, how could it manifest its presence? In fact to discuss this question properly we need to know how this spin- $\frac{3}{2}$ particle should couple to the other particles, which requires us to know which bosons and fermions could be associated under supersymmetry⁵. In any case, even without knowing that, we might already anticipate that the interactions of the gravitino, being proportional to the square root of the Newton constant $\sqrt{G_N} \simeq 10^{-19} \text{ GeV}^{-1}$, should be absolutely negligible in particle physics experiments. Quite surprisingly this may, however, not necessarily be true! We might be in a situation for which the gravitino is light, maybe even extremely light, so that this spin- $\frac{3}{2}$ particle would still interact very much like the massless spin- $\frac{1}{2}$ Goldstone fermion of global supersymmetry, according to the “equivalence theorem” of supersymmetry⁶. In that case we are led back to our initial question, where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry? But at this point we are in a position to answer, the direct detectability of the gravitino depending crucially on the value of its mass $m_{3/2}$, itself fixed by that of the supersymmetry breaking scale $\sqrt{d} = \Lambda_{ss}$ ^{6,18}.

In any case, much before getting to the Supersymmetric Standard Model, and irrespective of the question of supersymmetry breaking, the crucial question, if supersymmetry is to be relevant in particle physics, is:

Q3 : *Which bosons and fermions could be related by supersymmetry ?* (4)

But there seems to be no answer since known bosons and fermions do not appear to have much in common – excepted, maybe, for the photon and the neutrino. This track deserved to be explored⁴, but one cannot really go very far in this direction. In a more general way the number of (known) degrees of freedom is significantly larger for the fermions (now 90, for three families of quarks and leptons) than for the bosons (27 for the gluons, the photon and the W^\pm and Z gauge bosons, ignoring for the moment the spin-2 graviton, and the still-undiscovered Higgs boson). And these fermions and bosons have very different gauge symmetry properties!

Furthermore supersymmetric theories also involve, systematically, self-conjugate Majorana spinors – unobserved in Nature – while the fermions that we know all appear as Dirac fermions carrying conserved B and L quantum numbers. This leads to the question

Q4 : *How could one define (conserved) baryon and lepton numbers, in a supersymmetric theory ?* (5)

These quantum numbers, presently known to be carried by fundamental fermions only, not by bosons, seem to appear in Nature as *intrinsically-fermionic* numbers. Such a feature cannot be maintained in a supersymmetric theory, and one has to accept the (then rather heretic) idea of

attributing baryon and lepton numbers to fundamental bosons, as well as to fermions. These new bosons carrying B or L are the superpartners of the spin- $\frac{1}{2}$ quarks and leptons, namely the now-familiar (although still unobserved) spin-0 *squarks* and *sleptons*. Altogether, all known particles should be associated with new *superpartners*⁵.

Of course nowadays we are so used to deal with spin-0 squarks and sleptons, carrying baryon and lepton numbers almost by definition, that we can hardly imagine this could once have appeared as a problem. Its solution went through the acceptance of the idea of attributing baryon or lepton numbers to a large number of new fundamental bosons. But if such new spin-0 squarks and sleptons are introduced, their direct (Yukawa) exchanges between ordinary quarks and leptons, if allowed, could lead to an immediate disaster, preventing us from getting a theory of electroweak and strong interactions mediated by spin-1 gauge bosons, and not spin-0 particles, with conserved B and L quantum numbers! This may be expressed by the following question

$$\text{Q5 :} \quad \begin{array}{l} \textit{How can we avoid unwanted interactions} \\ \textit{mediated by spin-0 squark and slepton exchanges?} \end{array} \quad (6)$$

Fortunately, we can naturally avoid such unwanted interactions, thanks to R -parity (a remnant of the continuous $U(1)$ R -symmetry) which, if present, guarantees that squarks and sleptons *cannot* be directly exchanged between ordinary quarks and leptons, allowing for conserved baryon and lepton numbers in supersymmetric theories.

3 Continuous R -invariance and electroweak symmetry breaking (from an early attempt to relate the photon and the neutrino).

Let us now return to an early attempt at relating *existing* bosons and fermions together^{4e}, also at the origin of the definition of the continuous R -invariance (the discrete version of which leading to R -parity). It also showed how one can break spontaneously the $SU(2) \times U(1)$ electroweak gauge symmetry in a supersymmetric theory, using (in a modern language) a pair of chiral doublet Higgs superfields that would now be called H_1 and H_2 . This involves a mixing angle initially called δ but now known as β , defined by

$$\tan \beta = \frac{v_2}{v_1} . \quad (7)$$

The fermions of this early supersymmetric model, which are in fact gaugino-higgsino mixtures, should no longer be considered as lepton candidates, but became essentially the “charginos” and “neutralinos” of the Supersymmetric Standard Model^{5,6}.

Despite the general lack of similarities between known bosons and fermions, we tried as an exercise to see how far one could go in attempting to relate the spin-1 photon with a spin- $\frac{1}{2}$ neutrino. If we want to attempt to identify the companion of the photon as being a “neutrino”, despite the fact that it initially appears as a self-conjugate Majorana fermion, we need to understand how this particle could carry a conserved quantum number that we might interpret as a “lepton” number. This was made possible through to the definition of *a continuous $U(1)$ R -invariance*⁴, which also guaranteed the masslessness of this “neutrino” (“ ν_L ”, carrying +1 unit of R), by acting chirally on the Grassmann coordinate θ which appears in the expression of the various

^eThis model is reminiscent of a presupersymmetry two-Higgs-doublet model¹⁹ which turned out to be very similar to supersymmetric gauge theories, with Yukawa and φ^4 interactions restricted by a continuous Q -invariance, ancestor of the continuous R -invariance of supersymmetric theories.

gauge and chiral superfields. The supersymmetry generator Q_α carries one unit of the corresponding additive conserved quantum number, called R (so that one has $\Delta R = \pm 1$ between a boson and a fermion related by supersymmetry).

Attempting to relate the photon with one of the neutrinos could only be an exercise of limited validity. The would-be “neutrino”, in particular, while having in this model a $V - A$ coupling to its associated “lepton” and the charged W^\pm boson, was in fact what we would now call a “photino”, not directly coupled to the Z boson! Still this first attempt, which essentially became a part of the Supersymmetric Standard Model, illustrated how one can break spontaneously a $SU(2) \times U(1)$ gauge symmetry in a supersymmetric theory, through an electroweak breaking induced by a *pair of chiral doublet Higgs superfields*, now known as H_1 and H_2 ! (Using only a single doublet Higgs superfield would have left us with a massless charged chiral fermion, which is, evidently, unacceptable.) Our previous charged “leptons” were in fact what we now call two winos, or charginos, obtained from the mixing of charged gaugino and higgsino components, as given by the mass matrix

$$\mathcal{M} = \begin{pmatrix} (m_2 = 0) & \frac{g v_2}{\sqrt{2}} = m_W \sqrt{2} \sin \beta \\ \frac{g v_1}{\sqrt{2}} = m_W \sqrt{2} \cos \beta & \mu = 0 \end{pmatrix}, \quad (8)$$

in the absence of a direct higgsino mass that would have originated from a $\mu H_1 H_2$ mass term in the superpotential^f. The whole construction showed that one could deal elegantly with elementary spin-0 Higgs fields (not a very popular ingredient at the time), in the framework of spontaneously-broken supersymmetric theories. Quartic Higgs couplings are no longer completely arbitrary, but fixed by the values of the gauge coupling constants – here the electroweak couplings g and g' – through the following “ D -terms” (i.e. $\frac{\bar{D}^2}{2} + \frac{D'^2}{2}$) in the scalar potential given in⁴ g :

$$\begin{aligned} V_{\text{Higgs}} &= \frac{g^2}{8} (h_1^\dagger \vec{\tau} h_1 + h_2^\dagger \vec{\tau} h_2)^2 + \frac{g'^2}{8} (h_1^\dagger h_1 - h_2^\dagger h_2)^2 + \dots \\ &= \frac{g^2 + g'^2}{8} (h_1^\dagger h_1 - h_2^\dagger h_2)^2 + \frac{g^2}{2} |h_1^\dagger h_2|^2 + \dots \end{aligned} \quad (9)$$

This is precisely the quartic Higgs potential of the “minimal” version of the Supersymmetric Standard Model, the so-called MSSM, with its quartic Higgs coupling constants equal to

$$\frac{g^2 + g'^2}{8} \quad \text{and} \quad \frac{g^2}{2}. \quad (10)$$

Further contributions to this quartic Higgs potential also appear in the presence of additional superfields, such as the neutral singlet chiral superfield N already introduced in this model, which will play an important rôle in the NMSSM, i.e. in “next-to-minimal” or “non-minimal” versions of the Supersymmetric Standard Model. Charged Higgs bosons (now called H^\pm) are present in this framework, as well as several neutral ones. Their mass spectrum depends on the details of the supersymmetry breaking mechanism considered: soft-breaking terms, possibly “derived from supergravity”, presence or absence of extra- $U(1)$ gauge fields and/or additional chiral superfields, rôle of radiative corrections, etc..

^fThis $\mu H_1 H_2$ term, which would have broken explicitly the continuous $U(1)$ R -invariance then intended to be associated with the “lepton” number conservation law, was already replaced by a $\lambda H_1 H_2 N$ trilinear coupling involving an *extra neutral singlet chiral superfield* N .

^gWith a different denomination for the two Higgs doublets, such that $\varphi'' \mapsto h_1$, $(\varphi')^c \mapsto h_2$, $\tan \delta = v'/v'' \mapsto \tan \beta = v_2/v_1$.

4 The Supersymmetric Standard Model.

These two Higgs doublets are precisely the two doublets used in 1977 to generate the masses of charged leptons and down quarks, and of up quarks, in supersymmetric extensions of the standard model⁵. Note that at the time having to introduce Higgs fields was generally considered as rather unpleasant. While one Higgs doublet was taken as probably unavoidable to get to the standard model or at least simulate the effects of the spontaneous breaking of the electroweak symmetry, having to consider two Higgs doublets, necessitating charged Higgs bosons as well as several neutral ones, was usually considered as a too heavy price, in addition to the “doubling of the number of particles”, once considered as an indication of the irrelevance of supersymmetry. As a matter of fact considerable work was devoted for a time on attempts to avoid fundamental spin-0 Higgs fields, before returning to fundamental Higgses, precisely in this framework of supersymmetry.

In the previous $SU(2) \times U(1)$ model⁴, it was impossible to view seriously for very long “gaugino” and “higgsino” fields as possible building blocks for our familiar lepton fields. This led us to consider that all quarks and leptons ought to be associated with new bosonic partners, the *spin-0 squarks and sleptons*. Gauginos and higgsinos, mixed together by the spontaneous breaking of the electroweak symmetry, correspond to a new class of fermions, now known as “charginos” and “neutralinos”. In particular, the partner of the photon under supersymmetry, which cannot be identified with any of the known neutrinos, should be viewed as a new “photonic neutrino”, the *photino*; the fermionic partner of the gluon octet is an octet of self-conjugate Majorana fermions called *gluinos*, etc. – although at the time *colored fermions* belonging to *octet* representations of the color $SU(3)$ gauge group were generally believed not to exist (to the point that one could think of using the absence of such particles as a general constraint to select admissible grand-unified theories²⁰).

The two doublet Higgs superfields H_1 and H_2 generate quark and lepton masses^{5 h} in the usual way, through the familiar trilinear superpotential

$$\mathcal{W} = h_e H_1 \cdot \bar{E} L + h_d H_1 \cdot \bar{D} Q - h_u H_2 \cdot \bar{U} Q \quad . \quad (11)$$

L and Q denote the left-handed doublet lepton and quark superfields, and \bar{E} , \bar{D} and \bar{U} left-handed singlet antilepton and antiquark superfields. The vacuum expectation values of the two Higgs doublets described by H_1 and H_2 generate charged-lepton and down-quark masses, and up-quark masses, given by $m_e = h_e v_1/2$, $m_d = h_d v_1/2$, and $m_u = h_u v_2/2$, respectively. This constitutes the basic structure of the **Supersymmetric Standard Model**, which involves, at least, the ingredients shown in Table 1. Other ingredients, such as a direct $\mu H_1 H_2$ direct mass term in the superpotential, or an extra singlet chiral superfield N with a trilinear superpotential coupling $\lambda H_1 H_2 N + \dots$ possibly acting as a replacement for a direct $\mu H_1 H_2$ mass term⁴, and/or extra $U(1)$ factors in the gauge group (which could have been responsible for spontaneous supersymmetry breaking) may or may not be present, depending on the particular version of the Supersymmetric Standard Model considered.

^hThe correspondance between earlier notations for doublet Higgs superfields, and modern ones, is as follows:

$$\begin{array}{ccc} S = \begin{pmatrix} S^0 \\ S^- \end{pmatrix} \text{ and } T = \begin{pmatrix} T^0 \\ T^- \end{pmatrix} & \longrightarrow & H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ and } H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \\ \text{(left-handed)} & & \text{(both left-handed)} \end{array}$$

Furthermore, we originally denoted, generically, by S_i , left-handed, and T_j , right-handed, the chiral superfields describing the left-handed and right-handed spin- $\frac{1}{2}$ quark and lepton fields, together with their spin-0 partners.

Table 1: The basic ingredients of the Supersymmetric Standard Model.

1)	the three $SU(3) \times SU(2) \times U(1)$ gauge superfield representations;
2)	the chiral quark and lepton superfields corresponding to the three quark and lepton families;
3)	the two doublet Higgs superfields H_1 and H_2 responsible for the spontaneous electroweak symmetry breaking, and the generation of quark and lepton masses through
4)	the trilinear superpotential (11) .

Table 2: Minimal particle content of the Supersymmetric Standard Model.

Spin 1	Spin 1/2	Spin 0
gluons g photon γ	gluinos \tilde{g} photino $\tilde{\gamma}$	
<hr/> W^\pm Z	<hr/> winos $\tilde{W}_{1,2}^\pm$ zinos $\tilde{Z}_{1,2}$ higgsino \tilde{h}^0	<hr/> H^\pm H h, A } Higgs bosons
	leptons l quarks q	sleptons \tilde{l} squarks \tilde{q}

In any case, independently of the details of the supersymmetry breaking mechanism ultimately considered, we obtain the following minimal particle content of the Supersymmetric Standard Model, given in Table 2. Each spin- $\frac{1}{2}$ quark q or charged lepton l^- is associated with *two* spin-0 partners collectively denoted by \tilde{q} or \tilde{l}^- , while a left-handed neutrino ν_L is associated with a *single* spin-0 sneutrino $\tilde{\nu}$. We have ignored for simplicity further mixings between the various “neutralinos” described by neutral gaugino and higgsino fields, denoted in this table by $\tilde{\gamma}$, $\tilde{Z}_{1,2}$, and \tilde{h}^0 . More precisely, all such models include four neutral Majorana fermions at least, corresponding to mixings of the fermionic partners of the two neutral $SU(2) \times U(1)$ gauge bosons (usually denoted by \tilde{Z} and $\tilde{\gamma}$, or \tilde{W}_3 and \tilde{B}) and of the two neutral higgsino components (\tilde{h}_1^0 and \tilde{h}_2^0). Non-minimal models also involve additional gauginos and/or higgsinos.

5 About supersymmetry breaking, and the way from R -invariance to R -parity.

Let us now return to the definition of the continuous R -symmetry, and discrete R -parity, transformations. R -parity is associated with a Z_2 subgroup of the group of continuous $U(1)$ R -symmetry transformations, acting on the gauge superfields and the two doublet Higgs superfields H_1 and H_2 as in ⁴, with their definition extended to quark and lepton superfields so that quarks and leptons carry $R = 0$, and squarks and sleptons, $R = \pm 1$ (more precisely, $R = +1$ for \tilde{q}_L, \tilde{l}_L , and $R = -1$ for \tilde{q}_R, \tilde{l}_R) ⁵. As we shall see later, R -parity appears in fact as the remnant of this continuous R -invariance when gravitational interactions are introduced ⁶, in the framework of local supersymmetry (supergravity). Either the continuous R -invariance, or simply its discrete version of R -parity, if imposed, naturally forbid the unwanted direct exchanges of the new squarks and sleptons between ordinary quarks and leptons.

These continuous $U(1)$ R -symmetry transformations, which act chirally on the anticommuting Grassmann coordinate θ appearing in the definition of superspace and superfields, act on the gauge and chiral superfields of the Supersymmetric Standard Model as follows:

$$\left\{ \begin{array}{ll} V(x, \theta, \bar{\theta}) \rightarrow V(x, \theta e^{-i\alpha}, \bar{\theta} e^{i\alpha}) & \text{for the } SU(3) \times SU(2) \times U(1) \text{ gauge superfields} \\ H_{1,2}(x, \theta) \rightarrow H_{1,2}(x, \theta e^{-i\alpha}) & \text{for the left-handed doublet Higgs superfields } H_1 \text{ and } H_2 \\ S(x, \theta) \rightarrow e^{i\alpha} S(x, \theta e^{-i\alpha}) & \text{for the left-handed (anti)quark and lepton superfields} \\ & Q, \bar{U}, \bar{D}, L, \bar{E} . \end{array} \right. \quad (12)$$

They are defined so as not to act on ordinary particles, which have $R = 0$, while their superpartners have, therefore, $R = \pm 1$. They allow us to distinguish between two separate sectors of R -even and R -odd particles. R -even particles include the gluons, photon, W^\pm and Z gauge bosons, the various Higgs bosons, the quarks and leptons – and the graviton. R -odd particles include their superpartners, i.e. the gluinos and the various neutralinos and charginos, squarks and sleptons – and the gravitino (cf. Table 3). According to this first definition, R -parity simply appears as the parity of the additive quantum number R , as given by the expression ⁷:

$$R\text{-parity } R_p = (-1)^R = \begin{cases} +1 & \text{for ordinary particles,} \\ -1 & \text{for their superpartners.} \end{cases} \quad (13)$$

But why should we limit ourselves to the discrete R -parity symmetry, rather than considering its full continuous parent R -invariance ? This *continuous* $U(1)$ R -invariance, from which R -parity has emerged, is indeed a symmetry of all four necessary basic building blocks of the Supersymmetric Standard Model ⁵:

- 1) the Lagrangian density for the $SU(3) \times SU(2) \times U(1)$ gauge superfields;
- 2) the $SU(3) \times SU(2) \times U(1)$ gauge interactions of the quark and lepton superfields;
- 3) the $SU(2) \times U(1)$ gauge interactions of the two chiral doublet Higgs superfields H_1 and H_2 responsible for the electroweak symmetry breaking;
- 4) and the trilinear “superYukawa” interactions (11) responsible for quark and lepton masses. Indeed this trilinear superpotential transforms under the continuous R -symmetry (12) with “ R -weight” $n_W = \sum_i n_i = 2$, i.e. according to

$$\mathcal{W}(x, \theta) \rightarrow e^{2i\alpha} \mathcal{W}(x, \theta e^{-i\alpha}) ; \quad (14)$$

Table 3: R -parities in the Supersymmetric Standard Model.

Bosons	Fermions
gauge and Higgs bosons graviton $(R = 0)$ $R\text{-parity } +$	gauginos and higgsinos gravitino $(R = \pm 1)$ $R\text{-parity } -$
sleptons and squarks $(R = \pm 1)$ $R\text{-parity } -$	leptons and quarks $(R = 0)$ $R\text{-parity } +$

its auxiliary “ F -component” (obtained from the coefficient of the bilinear $\theta\theta$ term in the expansion of \mathcal{W}), is therefore R -invariant, generating R -invariant interaction terms in the Lagrangian densityⁱ.

However, an unbroken continuous R -invariance, which acts chirally on the Majorana octet of gluinos,

$$\tilde{g} \rightarrow e^{\gamma_5 \alpha} \tilde{g} . \quad (15)$$

would constrain them to remain massless, even after a (spontaneous) breaking of the supersymmetry. We would then expect the existence of relatively light “ R -hadrons”^{8,9} made of quarks, antiquarks and gluinos, which have not been observed. In fact we know today that gluinos, if they do exist, should be rather heavy, requiring a significant breaking of the continuous R -invariance, in addition to the necessary breaking of the supersymmetry. Once the continuous R -invariance is abandoned, and supersymmetry is spontaneously broken, radiative corrections do indeed allow for the generation of gluino masses²¹, a point to which we shall return later.

Furthermore, the necessity of generating a mass for the Majorana spin- $\frac{3}{2}$ *gravitino*, once *local* supersymmetry is spontaneously broken, also forces us to abandon the continuous R -invariance, in favor of the discrete R -parity symmetry, thereby also allowing for gluino and other gaugino masses, at the same time as the gravitino mass $m_{3/2}$, as already noted in 1977⁶. (A third reason for abandoning the continuous R -symmetry could now be the non-observation at LEP of a charged *wino* – also called *chargino* – lighter than the W^\pm , that would exist in the case of a continuous $U(1)$ R -invariance^{4,5}, as shown by the mass matrix \mathcal{M} of eq.(8); the just-discovered τ^- particle could tentatively be considered, in 1976, as a possible light wino/chargino candidate, before it got clearly identified as a sequential heavy lepton.)

Once we drop the continuous R -invariance in favor of its discrete R -parity version, we may ask how general is this notion of R -parity, and, correlatively, are we *forced* to have this R -parity conserved? As a matter of fact, there is from the beginning a close connection between R -parity and baryon and lepton number conservation laws, which has its origin in our desire

ⁱNote, however, that a direct Higgs superfield mass term $\mu H_1 H_2$ in the superpotential, which has R -weight $n = 0$, does *not* lead to interactions which are invariant under the continuous R symmetry; but it gets in general reallocated, as for example in the MSSM, as soon as the continuous R symmetry gets reduced to its discrete version of R -parity.

to get supersymmetric theories in which B and L could be conserved, and, at the same time, to avoid unwanted exchanges of spin-0 squarks and sleptons. Actually the superpotential of the theories discussed in Ref. ⁵ was constrained from the beginning, for that purpose, to be an *even* function of the quark and lepton superfields. *Odd* superpotential terms, which would have violated the “matter-parity” symmetry $(-1)^{(3B+L)}$, were excluded, to be able to recover B and L conservation laws, and avoid direct Yukawa exchanges of spin-0 squarks and sleptons between ordinary quarks and leptons. Tolerating unnecessary superpotential terms which are *odd* functions of the quark and lepton superfields (i.e. R_p -violating terms), does create, in general, immediate problems with baryon and lepton number conservation laws (most notably, a much too fast proton instability, if both B and L violations are simultaneously allowed).

This intimate connection between R -parity and B and L conservation laws can be made quite obvious by noting that for usual particles $(-1)^{2S}$ coincides with $(-1)^{3B+L}$, so that the R -parity (13) may be reexpressed in terms of the spin S and the “matter-parity” $(-1)^{3B+L}$, as follows ⁸:

$$R\text{-parity} = (-1)^{2S} (-1)^{3B+L} . \quad (16)$$

This may also be written as $(-1)^{2S} (-1)^{3(B-L)}$, showing that this discrete symmetry may still be conserved even if baryon and lepton numbers are separately violated, as long as their difference $(B - L)$ remains conserved, at least modulo 2.

The R -parity symmetry operator may also be viewed as a non-trivial geometrical discrete symmetry associated with a reflection of the anticommuting fermionic Grassmann coordinate, $\theta \rightarrow -\theta$, in superspace ²². This R -parity operator plays an essential rôle in the discussion of the experimental signatures of the new particles. A conserved R -parity guarantees that *the new spin-0 squarks and sleptons cannot be directly exchanged* between ordinary quarks and leptons, as well as the absolute stability of the “lightest supersymmetric particle” (or LSP), a good candidate for non-baryonic Dark Matter in the Universe.

Let us come back to the question of supersymmetry breaking, which still has not received a definitive answer yet. The inclusion, in the Lagrangian density, of universal soft supersymmetry breaking terms for all squarks and sleptons,

$$- \sum_{\tilde{q}, \tilde{l}} m_0^2 (\tilde{q}^\dagger \tilde{q} + \tilde{l}^\dagger \tilde{l}) , \quad (17)$$

was already considered in 1976. But it was also understood that such terms should in fact be generated by a spontaneous supersymmetry breaking mechanism, especially if supersymmetry is to be realized locally. As a matter of fact they were first spontaneously generated with the help of the “ D -term” associated with an *extra* $U(1)$ gauge symmetry, acting *axially* on leptons and quarks fields – thereby allowing to lift the mass² of *both* “left-handed” and “right-handed” slepton and squark fields, by the same positive amount. When the gauge coupling constant g of this (still unbroken) extra $U(1)$ was taken to be very small, the supersymmetry was spontaneously broken “at a very high scale” $\sqrt{d} = \Lambda_{ss} \gg m_W$. In the limit $g \rightarrow 0$, the corresponding Goldstone fermion – the gaugino of the extra $U(1)$ – became completely decoupled, but supersymmetry was still broken with heavy slepton and squark masses; the breaking was then explicit instead of spontaneous, although only softly through the dimension 2 mass terms (17).

To get a true spontaneous breaking of the supersymmetry with a physically coupled goldstino (of course to be subsequently “eaten” by the spin- $\frac{3}{2}$ gravitino) rather than an explicit (although

soft) one, as well as a spontaneous breaking of the extra $U(1)$ symmetry, and also to render, at the same time, the superpotential (11) invariant under this extra $U(1)$ symmetry so that it can actually be responsible for the generation of lepton and quark masses, we modified the definition of this extra $U(1)$ so that it also acts on the Higgs superfields H_1 and H_2 as well as on lepton and quark superfields, as follows:

$$\left\{ \begin{array}{ll} V(x, \theta, \bar{\theta}) \rightarrow V(x, \theta, \bar{\theta}) & \text{for the } SU(3) \times SU(2) \times U(1) \text{ gauge superfields;} \\ H_{1,2}(x, \theta) \rightarrow e^{-i\alpha} H_{1,2}(x, \theta) & \text{for the left-handed doublet Higgs superfields } H_1 \text{ and } H_2 \\ S(x, \theta) \rightarrow e^{i\frac{\alpha}{2}} S(x, \theta) & \text{for the left-handed (anti)quark and (anti)lepton} \\ & \text{superfields } Q, \bar{U}, \bar{D}, L, \bar{E} . \end{array} \right. \quad (18)$$

This newly-defined extra $U(1)$ (acting on the two Higgs doublets so that it gets spontaneously broken together with the electroweak symmetry), is now a symmetry of the trilinear superpotential interactions (11), so that lepton and quark can now acquire masses in a way compatible with the spontaneous supersymmetry breaking mechanism used. This extra $U(1)$ is associated, in the simplest case of eq. (18), with a purely axial extra $U(1)$ current for all quarks and charged leptons. Gauging such an extra $U(1)$, which must in any case be different from the weak-hypercharge $U(1)$, is in fact necessary²³, if one intends to generate large *positive* mass² for *all* squarks ($\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$) and sleptons, at the classical level, in a spontaneously-broken globally supersymmetric theory (otherwise we could not avoid squarks having negative or at best very small mass²). But this method of spontaneous supersymmetry breaking also led to several difficulties. In addition to the question of anomalies, it required new neutral current interactions beyond those of the Standard Model. This was fine at the time, in 1977, but such interactions did not show up while the $SU(2) \times U(1)$ neutral current structure of the Standard Model got experimentally confirmed. This mechanism also left us with the question of generating large gluino masses. Altogether, the gauging of an extra $U(1)$ no longer appears as an appropriate way to generate large superpartner masses. One now uses again, in general, soft supersymmetry-breaking terms²⁴ generalizing those of eq. (17) – possibly “induced by supergravity” – which essentially serve as a parametrization of our ignorance about the true mechanism of supersymmetry breaking chosen by Nature to make superpartners heavy.

Let us return to gluino masses. As we said before continuous R -symmetry transformations act *chirally* on gluinos, so that an unbroken R -invariance would require them to remain massless, even after a spontaneous breaking of the supersymmetry! Thus the need, once it became experimentally clear that massless or even light gluinos could not be tolerated, to generate a gluino mass either from radiative corrections²¹, or from supergravity (see already⁶), with, in both cases, the continuous R -invariance reduced to its discrete R -parity subgroup.

In the framework of global supersymmetry it is not so easy to generate large gluino masses. Even if global supersymmetry is spontaneously broken, and if the continuous R -symmetry is not present, it is still in general rather difficult to obtain large masses for gluinos, since: **i)** no direct gluino mass term is present in the Lagrangian density; and **ii)** no such term may be generated spontaneously, at the tree approximation, gluino couplings involving *colored* spin-0 fields. A gluino mass may then be generated by radiative corrections involving a new sector of quarks sensitive to the source of supersymmetry breaking²¹, that would now be called “messenger quarks”, but **iii)** this can only be through diagrams which “know” both about: **a)** the spontaneous breaking of the global supersymmetry, through some appropriately-generated v.e.v.’s for auxiliary components, $\langle D \rangle$, $\langle F \rangle$ or $\langle G \rangle$ ’s; **b)** the existence of superpotential interactions which do not preserve the continuous $U(1)$ R -symmetry. Such radiatively-generated

gluino masses, however, generally tend to be rather small, unless one introduces, in some often rather complicated “hidden sector”, very large mass scales $\gg m_W$.

Fortunately gluino masses may also result directly from supergravity, as already observed in 1977⁶. Gravitational interactions require, within local supersymmetry, that the spin-2 graviton be associated with a spin-3/2 partner¹⁷, the gravitino. Since the gravitino is the fermionic gauge particle of supersymmetry it must acquire a mass, $m_{3/2}$ ($= \kappa d/\sqrt{6} \approx d/m_{\text{Planck}}$), as soon as the local supersymmetry gets spontaneously broken. Since the gravitino is a self-conjugate Majorana fermion its mass breaks the continuous R -invariance which acts chirally on it, just as for the gluinos, forcing us to abandon the continuous $U(1)$ R -invariance, in favor of its discrete R -parity subgroup. In particular, in the presence of a spin- $\frac{3}{2}$ gravitino mass term $m_{3/2}$, which corresponds to $\Delta R = \pm 2$, the “left-handed sfermions” \tilde{f}_L , which carry $R = +1$, can mix with the right-handed ones \tilde{f}_R , carrying $R = -1$, through mixing terms having $\Delta R = \pm 2$, which may naturally (but not necessarily) be of order $m_{3/2} m_f$. Supergravity theories offer, in addition, a natural framework in which to include direct gaugino Majorana mass terms

$$-\frac{i}{2} m_3 \tilde{G}_a \tilde{G}_a - \frac{i}{2} m_2 \tilde{W}_a \tilde{W}_a - \frac{i}{2} m_1 \tilde{B} \tilde{B} , \quad (19)$$

which also correspond to $\Delta R = \pm 2$. The mass parameters m_3 , m_2 and m_1 , for the $SU(3) \times SU(2) \times U(1)$ gauginos, could naturally (but not necessarily) be of the same order as the gravitino mass $m_{3/2}$. Incidentally, once the continuous R -invariance is reduced to its discrete R -parity subgroup, a direct Higgs superfield mass term $\mu H_1 H_2$, which was not allowed by the continuous $U(1)$ R -symmetry, gets reallocated in the superpotential, as for example in the MSSM. The size of this supersymmetric μ parameter (which breaks explicitly both the continuous R -invariance (12) and the (global) extra $U(1)$ symmetry (18) may then be controlled by considering one or the other of these two symmetries. In general, irrespective of the supersymmetry breaking mechanism considered, one normally expects the various superpartners not to be too heavy, otherwise the corresponding new mass scale would tend to contaminate the electroweak scale, thereby *creating* a hierarchy problem in the Supersymmetric Standard Model. Superpartner masses are then normally expected to be naturally of the order of m_W , or at most in the $\sim \text{TeV}/c^2$ range.

The Supersymmetric Standard Model (“minimal” or not), with its R -parity symmetry (absolutely conserved, or not), provided the basis for the experimental searches for the new superpartners and Higgs bosons, starting with the first searches for gluinos and photinos, selectrons and smuons, at the end of the seventies. How the supersymmetry should actually be broken, if indeed it is a symmetry of Nature, is not known yet. Many good reasons to work on the Supersymmetric Standard Model and its various extensions have been discussed, dealing with supergravity, the high-energy unification of the gauge couplings, extended supersymmetry, new spacetime dimensions, superstrings, “ M -theory”, However, despite all the efforts made for more than twenty years to discover the new inos and sparticles, we are still waiting for experiments to disclose the missing half of the SuperWorld!

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